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Title: ON THE MEASUREMENT OF THE ELECTRON-NEUTRINO CORRELATION IN NEUTRON BETA DECAY

Author(s): J. David Bowman, P-23 MS H803

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J. David. Bowman

Los Alamos National Laboratory, Los Alamos, NM 87544, USA.

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J. David Bowman
Los Alamos National Laboratory, Los Alamos NM 87544

Abstract:
A new approach to the measurement of a, the electron-neutrino correlation, in neutron beta decay is presented. A precise measurement of a can lead to a precise determination of G_a/G_v. Coincidences between electrons and protons are detected in a field-expansion spectrometer. Both electrons and protons are detected in segmented Si detectors. The spectrometer configuration has a long, ~ 1 meter, drift distance for the proton. The electron energy and time of flight between the electron and proton are measured. We shown that by sorting the data on proton time of flight and electron energy, a can be determined with a statistical accuracy of $\sim 5.1/\sqrt{n}$, where n is the number of decays observed. The approach has a number of advantages. Thin-dead-layer segmented Si detectors are commercially available. There are no material apertures to determine the acceptance of the apparatus. The charged particles interact only with electric and magnetic fields before striking the detectors. Coincident detection of electrons and protons reduces backgrounds, and allows the *in situ* determination of backgrounds. In the analysis, it is not necessary to sort on the relative electron and proton direction and hence electron back scattering does not cause systematic uncertainties. A time of flight spectrum is obtained for each electron energy. Different parts of the spectra have different sensitivities to a. The parts of the spectra that are insensitive to a can be used to verify the accuracy of the electric and magnetic field determinations.

A reference design for the field expansion spectrometer is shown if Figure 1. Electrons and protons spiral around magnetic field lines and are guided to two 10 cm by 10 cm segmented Si detectors. The strength of the field in the center of the spectrometer is 4 T and near the Si detectors is 1 T. The field expansion decreases the angle between the momentum and the magnetic field lines and the particles strike the detectors at approximately normal angles. After the magnetic field expansion an electric field is applied to the particles so that the protons have enough energy to be detected in the Si detectors. The electric field reduces the energy of the electrons. The electric field must be applied after the magnetic field expansion so that the electrons acceptance does not depend on electron energy. For the reference design, all electrons that have energies above 70 KeV reach the detectors and deposit at least 30 KeV. There is a long drift region where the magnetic field is uniform so that the proton time of flight depends mainly on the component of the momentum along the field direction, z, and is insensitive to the location of the decay within the beam or to the magnitude of the momentum. After the drift region the protons are accelerated from ~400 eV to 30 KeV so that the time spent between the potential change and the detector is small compared to the time spent in the drift region. Electrons may be scattered from the Si detectors, but scattered electrons are guided back to one of the detectors and eventually all the electrons energy is deposited in the detectors. The segmented Si detectors form an image of the. The ends of the decay region are defined by the image of the beam on the detectors. The transverse migration of back scattered electrons is small because the radius of gyration is small, a few mm, and because the momentum of the electron decreases with each reflection. We estimate that rates between 100 and 1000 Hz can be obtained at NIST or HFIR. A sample of 10^9 events could be obtained in a 10^6-10^7 seconds leading to a determination of a to ~.2%.

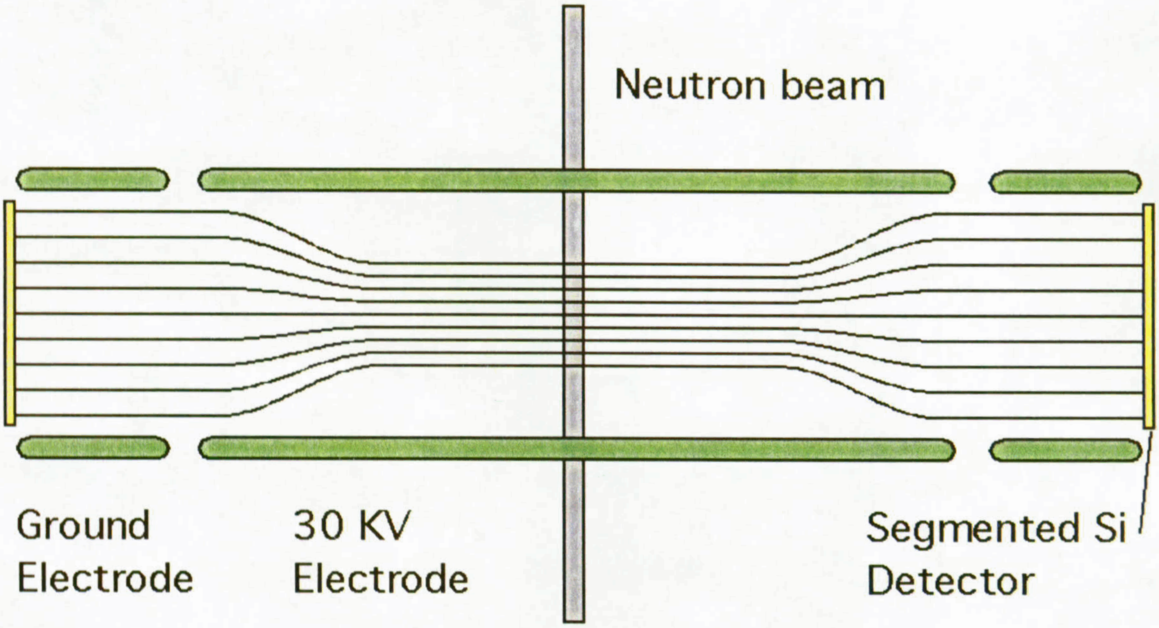

Figure 1. A schematic view of the field expansion spectrometer.

Figure 2. shows a plot of 1/vz(z) for two protons, one with its momentum initially in the z direction (upper curve) , and the other with its momentum at at 84 degrees. The times of flight are 34 and 27 μsec. Below we show that time differences of this size have little impact on the statistical error in a. First we consider an idealized spectrometer in which pz, the z component of the proton momentum, is measured and explain why the approach is efficient. Then we calculate the statistical error in a for a real spectrometer that measures TOF (the difference of proton time of flight and electron time of flight) and demonstrate that the increase in the error is small in going from pz to TOF. In order to measure the electron-spin correlation, A, it is necessary to determine which of the two detectors the electron struck first. This determination requires a long spectrometer and fast detectors. We show below that it is not necessary to determine the relative direction of the electron and proton in order to measure the electron-neutrino correlation. The TOF and electron energy are sufficient. The practical implication of combining the two directions is important. It is possible to obtain commercially segmented Si detectors with thin ion-implanted entrance windows. The sheet resistance of the ion-implanted junction is large and the large rise time (~50 nsec) makes fast timing impractical. The ability to use slow Si detectors makes the experiment feasible without new technology.

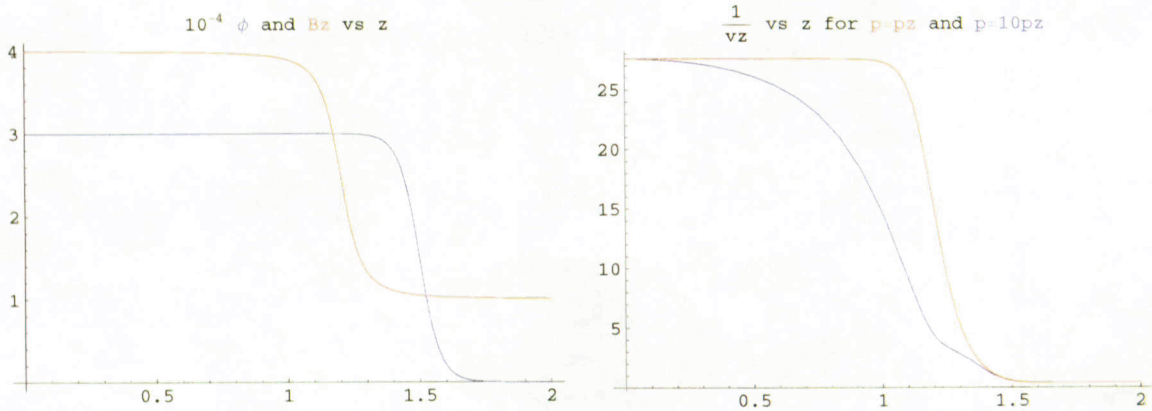

Figure 2 Plots of electric potential $\phi(z)$ (V) and magnetic field Bz(z) (T), and the inverse proton velocity 1/vz(z) (μsec/meter) as functions of z (meters).

The electron neutrino correlation expresses the dependence of decay rate on the angle between the neutrino and electron,

$$\mathrm{Cos}(\vartheta ev) = \mathrm{Cos}(\vartheta e)\mathrm{Cos}(\vartheta \nu) + \mathrm{Sin}(\vartheta e)\mathrm{Sin}(\vartheta \nu)\mathrm{Cos}(\varphi e - \varphi \nu).$$

It is not possible to measure the z component of the proton momentum, pz, but is useful to first imagine that it were possible in order to understand the idea of the proposed experiment. After the discussion based on pz, we show that TOF gives the same information as pz. The field-expansion spectrometer is azimuthally symmetric and the second term in $\mathrm{Cos}(\vartheta ev)$ does not influence the average rate of detected events as a function of electron energy, T_e, and pz. If we set $u = \mathrm{Cos}(\vartheta \nu)$ and $v = \mathrm{Cos}(\vartheta e)$, the average rate depends on $1 + a\,\beta\,\mathrm{Cos}(\vartheta ev)$ and $d\log(Y)/da = \beta\,\overline{\mathrm{Cos}(\vartheta ev)}$. Of course none of the angles are directly observed. If they were, the error in a for a given number of detected events would be $\sigma_a = \sqrt{3}/n\,\beta_{ave}^2 = 2.3/\sqrt{n}$. Averaging over the unobserved angles increases the error to $5.1/\sqrt{n}$. In the field-expansion spectrometer we trade well-known 4π acceptance with small detectors for a reduction in statistical sensitivity per $\sqrt{n}$.

Figure 3a. shows contours of $u\,v = \overline{\mathrm{Cos}(\vartheta ev)}$ vs u (horizontal) and v (vertical), The largest sensitivity occurs where $|u\,v|$ is large in the four corners of the plot. In the upper half of the plot, the electron goes towards positive z. Figure 3b. shows contours of pz vs u and v for an electron energy of 261 KeV. The proton recoils against the sum of the electron and neutrino momenta and the z component of the proton momentum is $pz = u\,|p\nu| + v\,|pe|$. pz is zero along the diagonal line passing through the origin. The proton goes towards negative z for the lighter regions and towards positive z for the darker regions. For each value of the electron energy, the neutrino energy is (approximately) determined by the conditions $|p\nu| + Te = Q - Tp$ and $Tp << Q$. Figure 3b. shows contours $u\,v$. Comparison of 3a. and 3b. demonstrates that selecting a value of pz places an approximate constraint on $u\,v$ and allows an efficient weighted average to be carried out to determine a from the pz (or TOF) spectra for each T_e.

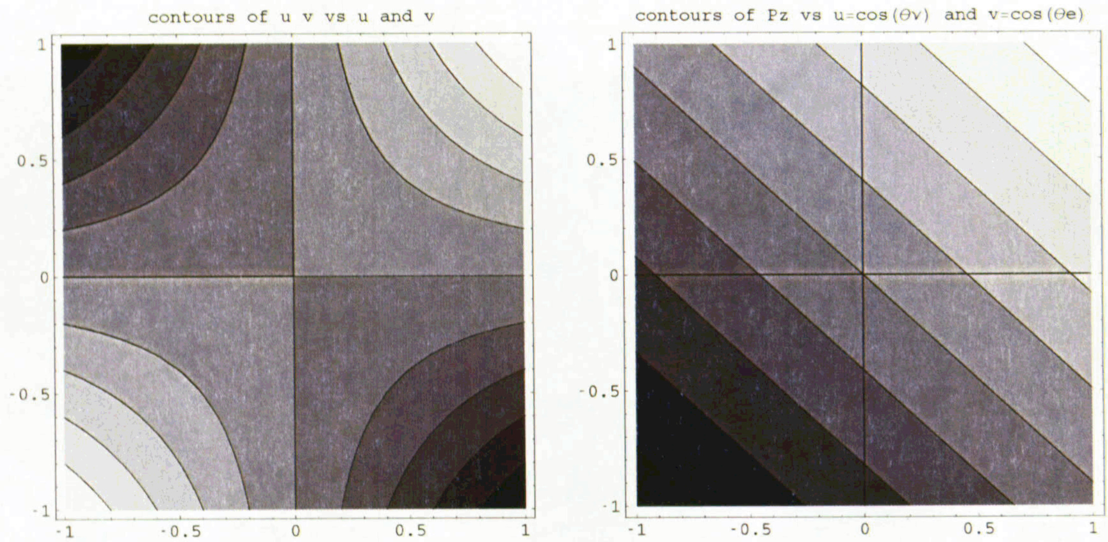

Figure 3a. on the left shows contours of $u\,v$ vs u (horizontal) and v (vertical). Figure 3b. shows contours of pz.

Figures 4a. and 4b. show the yield of events and the average of sensitivity of the rate to a, $\beta\,\overline{\mathrm{Cos}(\vartheta e\nu)}$ vs T_e and pz. The electron energy is constrained to have $T_e > 100$ KeV so that every electron is detected. The average sensitivity of the yield to a is large for large pz for the reasons discussed above. The events with large pz give the most information about a. When the electron energy is large, there is little information about a except for the largest pz, because when T_e is large the proton recoils against the electron. The events to the right of the diagonal on Figure 4b. have a small sensitivity to a and can be used to check the accuracy of the field maps. The systematic uncertainty in a may be of the same order as the accuracy of the field maps. Standard techniques of mapping magnetic fields are accurate to $\sim 10^{-4}$ and electric fields can be accurately calculated for a system of conductors at known potentials. Figures 4c. and 4d. show the yield and sensitivity for events where the electron and proton go in the same direction. There are two reasons that combining the classes of events where the proton goes in the same and opposite direction as the electron does not increase the error in a. The number of events where the proton and electron go in the same direction is small, 19% of the total. Furthermore, as can be seen by comparing 4b. and 4d. the shapes of the sensitivities to a are similar for the two classes of events. In fact, for T_e=236 KeV the neutrino and electron momenta are equal the line $pz = 0$ is at $3\pi/4$, and the shapes of $\beta\,\overline{\mathrm{Cos}(\vartheta e\nu)}$ vs pz are identical.

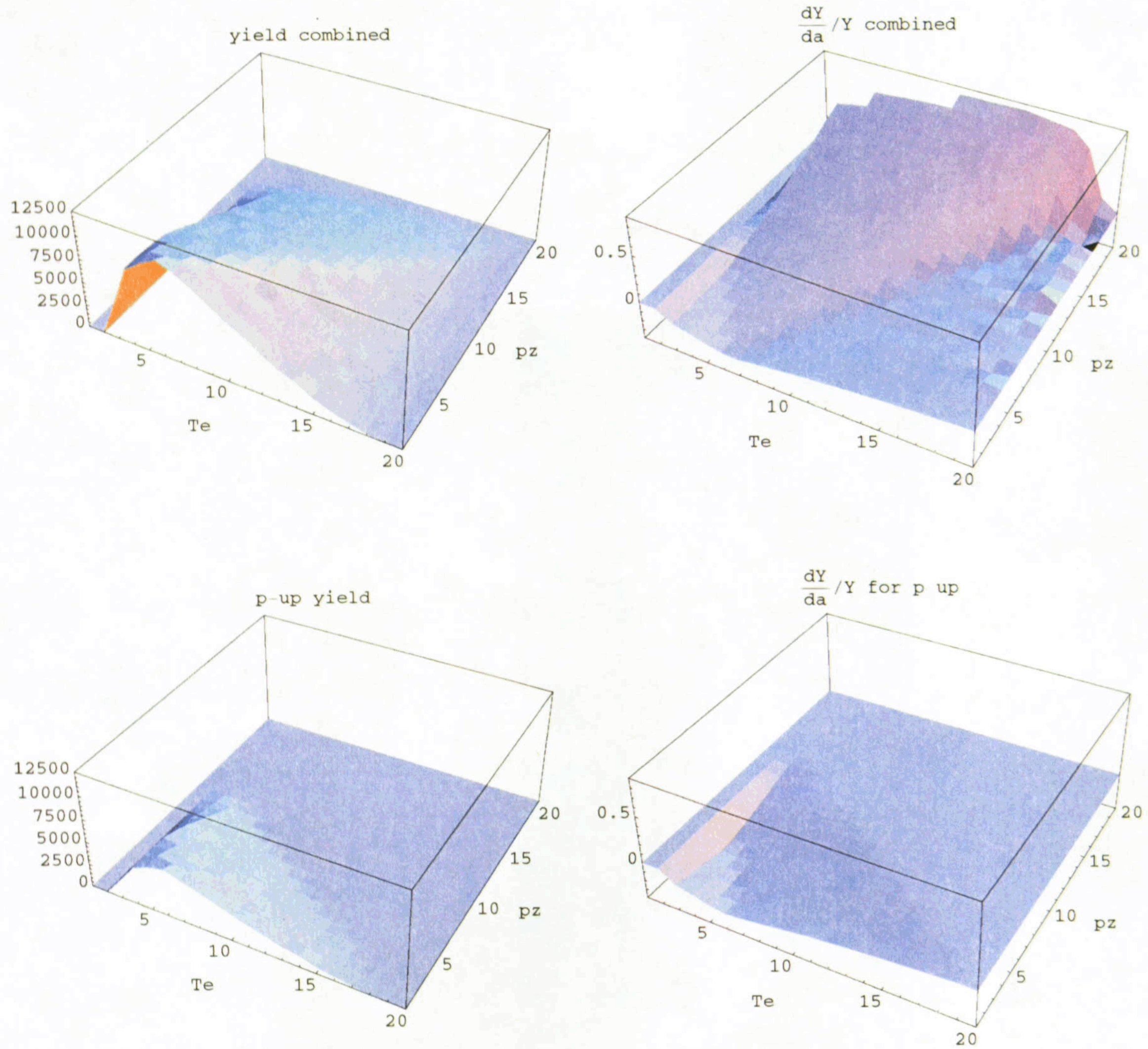

Figure 4a. Yield vs T_e and pz for all events. Figure 4b. The average sensitivity of the yield to a, $\beta\,\overline{\mathrm{Cos}(\vartheta e\nu)}$ vs T_e and pz for all events. Figure 4c. Yield vs T_e and pz for events where the proton and electron go in the same direction. Figure 4d. Sensitivity of the yield to a, for events where the proton and electron go in the same direction.

We performed a Monte-Carlo calculation of the error in a using 10^6 events binning the events on T_e and pz. The result for the error in a was $\sigma_a = 5.02/\sqrt{n}$ when the information on the relative electron and proton directions was included and $\sigma_a = 5.12/\sqrt{n}$ when the information was neglected. We calculated the error in a using 2 10^6 events binning on T_e and $1/TOF$. Although there is not a 1-1 correspondence between $1/\mathrm{TOF}$ and pz, the plots are very similar. The measurement of pz isolates the regions where $\beta\,\overline{\mathrm{Cos}(\vartheta e\nu)}$ is large. TOF depends on p as well as pz. However, where $\beta\,\overline{\mathrm{Cos}(\vartheta e\nu)}$ is large the dependence is weak. The result for the error was $\sigma_a = 5.02/\sqrt{n}$ when the information on the relative electron and proton directions was included and $\sigma_a = 5.11/\sqrt{n}$ when the information was neglected.

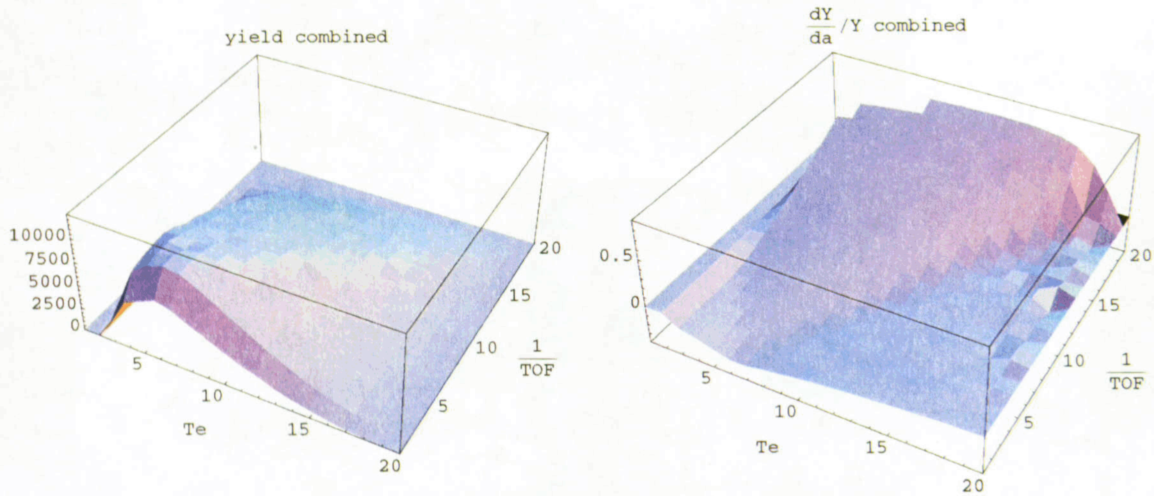

Figure 5. Yield and sensitivity for events binned on T_e and $1/\mathrm{TOF}$.

Conclusion:

We have shown that a field-expansion spectrometer with a long drift distance to measure proton time of flight is an attractive approach to measure the electron-neutrino correlation in neutron beta decay. The discussion has been primarily aimed at discussing statistical and systematic errors, but a precise measurement of a can lead to the determination of G_a/G_v. The statistical effectiveness $\sigma_a = 5.11/\sqrt{n}$ is favorable and the count rate is large. The approach avoids many of the potential sources of systematic uncertainty in other methods of determining G_a/G_v. It is not necessary to make a precise measurement of the neutron polarization. Backgrounds are greatly reduced by detecting electrons and protons in coincidence. The 4π acceptance of the spectrometer is well understood. The charged particles interact only with electric and magnetic fields before detection. Electron back scattering is not an issue, because it is not necessary to determine the relative directions of the electron and proton. We estimate a statistical uncertainty of a few 10^{-3} could be obtained in a 16^{6} - 10^{7} sec run at HFIR or NIST.